LES Modeling of Aerosol and Drizzle Effects in Marine Stratocumulus

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LONG-TERM GOALS

The development and improvement of cloud microphysical and radiative parameterizations for use in cloud and numerical forecast models

OBJECTIVES

The study of marine stratocumulus cloud microphysical and radiative processes using the high-resolution large eddy simulation (LES) model with explicit microphysics. We aim at refining parameterizations of microphysical and radiative processes based on better understanding of interactions between these processes and boundary layer thermodynamics.

Towards this goal, we investigate:

1) The effect of sea-salt aerosols produced by surface winds on boundary layer cloud microstructure and drizzle,
2) The formulation of cloud physics processes based on full moments of the drop spectra,
3) The development of a parameterization of the effective radius for drizzling marine stratocumulus.
4) The development of a new method for evaluating cloud radiative absorption.

APPROACH

The research is based on the CIMMS LES model of boundary layer stratocumulus clouds with explicit formulation of aerosol and drop size-resolving microphysics. The model has been thoroughly verified against observations from various field programs. The University of Oklahoma MS student, Mr. Yuri Shprits, performed LES experiments to investigate the effect of sea-salt aerosols produced by surface winds on cloud microstructure and drizzle. The University of Oklahoma PhD student, Mr. Alexei Belochitski, used the model generated cloud drop spectra to calculate the microphysical change rates of prognostic variables. The latter are required in the bulk formulation of cloud processes in numerical weather prediction models. In collaboration with Drs. E. Kassianov and Z. Kogan, we have employed LES simulations, as well as 3D Monte Carlo model to evaluate the effect of drizzle on cloud radiative properties.

WORK COMPLETED

We have completed the following tasks this year:

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **LES Modeling of Aerosol and Drizzle Effects in Marine Stratocumulus**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Oklahoma,,Norman,,OK, 73019**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The development and improvement of cloud microphysical and radiative parameterizations for use in cloud and numerical forecast models

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

1. Investigation of the combined effects of surface winds and aerosol concentrations, as well as BL thermodynamical parameters, on cloud drop microstructure and drizzle.
2. Derivation of bulk coagulation rates for full moments of the drop spectra, including drop number concentration, effective radius, precipitation flux, and radar reflectivity.
3. Developed a parameterization of the effective radius for drizzling marine stratocumulus.
4. Developed a new method for evaluating cloud radiative absorption.

RESULTS

1. The effects of surface winds on cloud microstructure and drizzle

Defining cloud microphysics and radiation parameters in numerical forecast models present an important, however quite a challenging problem. For instance, Martin et al (1994), O'Dowd et al (1996), among others, suggested analytical relations between the aerosol and cloud drop concentrations. These relations, however, need to be modified for surface wind conditions; the latter directly affect the concentration of sea-salt particles. We used an explicit microphysics LES model to investigate the role of total concentration and shape of the background non-sea-salt (*nss*) sulfate aerosol spectra under surface wind conditions of up to 17 m/s.

The series of nine experiments were conducted to simulate clouds in (1) a very clean air mass with low *nss* concentration of 70 cm^{-3}, (2) a polluted air mass with *nss* concentration of 230 cm^{-3}, and (3) an intermediate case with a lower than in (2) concentration of sulfate aerosols in the range 0.04-0.1µ (30 versus 110 cm^{-3}). Aitken nuclei in this size interval correspond to the range of critical supersaturations from 0.05% to 0.2%, which has the highest frequency of occurrence in a BL characterized by mean updraft velocity of about 0.3 – 0.4 m/s. For each of the three experiments, three more were conducted with surface wind speeds of 0, 10 and 17 m/s.

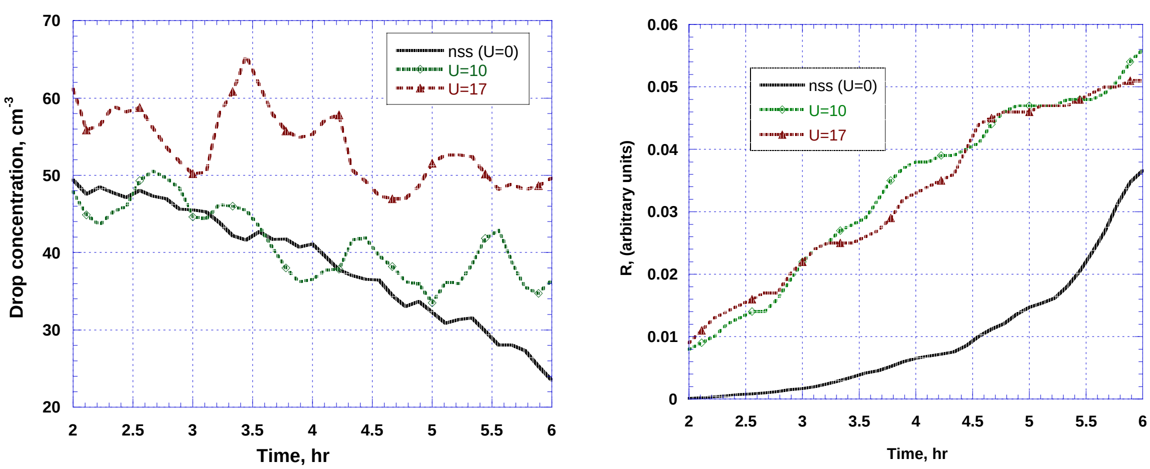

Fig. 1. Cloud drop concentration and drizzle is increased under higher surface winds U (ms^{-1}).

Fig. 1 shows evolution of the domain averaged drop concentration in a clean air mass. The addition of sea-salt particles increases the cloud drop concentration, most significantly (by 20-50%) at high surface winds (U=17 m/s). As the total number of sulfate and sea-salt particles is rather small (less than 80 cm^{-3} even at the initial stage of activation), it cannot substantially reduce the supersaturation and all the sea-salt, as well as sulfate particles are activated. Drizzle is easily formed in this clean air mass resulting in the drop concentration decrease with time.

The effect on cloud drop concentration depends not only on total ambient aerosol concentration, but also on concentration of sulfate particles in the 0.04-0.1μ range. Fig. 2 shows the effect in the experiment 3. The surface winds cause the decrease in drop concentration from 100 cm^{-3} to 70 cm^{-3}. The activation of sea-salt particles limits the growth of supersaturation and keeps sulfate particles smaller than 0.04 μ from activation. Interestingly, the effect is almost the same for U=10 and U=17 m/s, obviously due to negative feedbacks between drizzle and supersaturation. Initially, the former is larger at U=17 m/s. As a result, the decrease in drop concentration due to drizzle is more pronounced in this case. The lower drop concentration leads to larger supersaturations and an increase in CCN nucleation that may counterbalance the drop concentration decrease due to drizzle. In the *nss* case, the cloud is not drizzling. When sea-salt particles are produced by surface winds of 17 m/s, the maximum drizzle rate is an order of magnitude higher and drizzle is occupying about half of the domain. Drizzle initiated by sea-salt CCN affects dynamical parameters of the boundary layer. It changes the temperature and liquid water profile, which in turn affect updrafts. The domain averaged updraft velocity (not shown) in the *nss* case is roughly two times higher than in the sea-salt case. The change in the updraft velocity affects in-cloud supersaturation as well as CCN transport into the cloud layer.

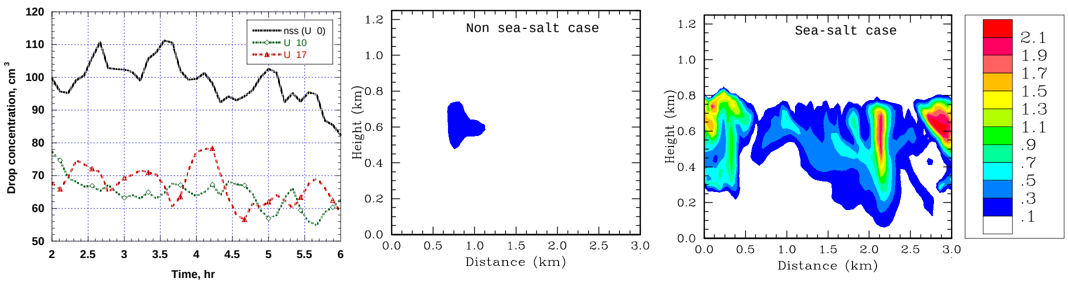

Fig. 2. In the more polluted air mass the cloud drop concentration is decreased from 100 to 70 cm^{-3} (left). Vertical cross-section of drizzle rates for nss and sea-salt (U=17) cases (middle and right panels).

Clearly, the surface winds affect the stratocumulus drop concentration in a complex way involving many feedbacks between the intensity of BL turbulence, intensity of drizzle, the total concentration and shape of the background CCN sulfate spectra. Model simulations showed that the total background sulfate concentration does not uniquely define the effect of surface winds. An accurate formulation of this effect should account for the shape of the background sulfate spectrum. In particular, it is important to account for the number concentration of Aitken nuclei in the radius range from 0.04 to 0.1 μ.

2. An integrated approach to parameterization of cloud physics processes

The conventional cloud physics parameterizations divide the total liquid water into cloud water (transported with an airflow) and rain water (having its own fall speed). The division is artificial, as observational and modeling data do not show a distinctive gap between small and large drops. As a result, the autoconversion and accretion rates are quite sensitive to the value of the threshold radius dividing cloud and rain water, though the severity of the errors depends on cloud type. The problem is better posed when the artificial division of total water into two parts is avoided altogether.

We developed a cloud physics parameterization based on the full moments of the drop spectra, as opposed to partial moments used in Kessler-type parameterizations. The set of full moments includes cloud drop concentration ***N***, cloud drop geometrical cross-section ***S***, liquid water content ***Q***, drizzle sedimentation flux ***P***, and radar reflectivity ***Z***. The ratio of ***Q*** to ***S*** is related to the drop effective radius, an important parameter needed for radiative calculations.

The condensation-evaporation rate can be written explicitly using drop condensational growth equation. The coagulation process in the new parameterization replaces the artificial processes of autoconversion and accretion. The rate of change for each moment due to coagulation is determined using regression analysis of the exact coagulation rates calculated from the CIMMS explicit microphysics LES model. The errors of parameterized expressions are an order of magnitude less than autoconversion rates errors in a conventional Kessler type parameterization.

The full moment parameterization has been implemented into the 3D dynamical framework of the CIMMS LES model where the errors of the parameterization can be assessed in a more realistic setting. The performance of the parameterization has been evaluated by comparing it with the solution given by explicit microphysical model. The preliminary experiment showed that the parameterization represents the main microphysical and dynamical structure of the cloud layer reasonably well. More testing of the parameterization is planned in the future by simulating a wide range of drizzling stratocumulus clouds.

3. Parameterization of the effective radius in marine stratocumulus

The cloud drop effective radius, R_e, is an important parameter in calculations of cloud radiative properties, as well as satellite retrievals of cloud microphysical characteristics. Numerous formulations of the effective radius have been developed for use in numerical models; however, none were designed for non-drizzling clouds. Based on LES simulations, we derived a parameterization of R_e for precipitating boundary layer clouds. The parameterized expression for R_e is sought as a function of the following set of variables: N - total drop concentration, Q - total liquid water content, and Z - radar reflectivity.

Martin et al (1994) using empirical data obtained a parameterization for R_e in the form $R_e^3 = k^{-1}R_{vol}^3$ where $k=0.8$ for non-drizzling marine clouds. For precipitating clouds, this parameterization performs rather poorly (rms error of 12%). Using regression analysis, we showed that the constant k is a function of variables Q and N. Marine stratus with more drizzle (smaller N or larger R_e) correspond to smaller values of k (Fig. 3). Our expression for k is consistent with results observed during INDOEX field program. McFarquhar and Heymsfield (2000) report values of k =0.60 for clean drizzling clouds, while for non-drizzling clouds k=0.85.

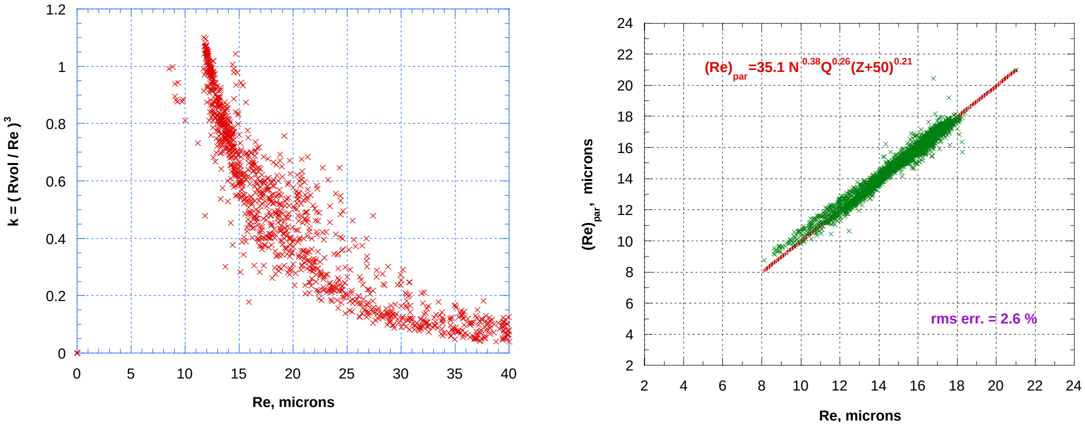

Fig. 3. Left panel: the constant k as a function of effective radius. Right panel: The scatter plots of $(R_e)_{par}$ defined as a function of three variables versus the benchmark value of R_e from the explicit microphysical model.

The accuracy of a two-variable parameterization can be increased if radar reflectivity factor *Z* is added as a third variable. In this case the rms error is reduced to 2.6% (Fig. 3). The three-variable parameterization can be used for a wide range of ambient conditions characterizing marine drizzling stratocumulus. Finally, we also confirmed that a parameterization based on partial moments is less accurate, mainly because of the uncertainty in the definition of the threshold radius dividing the cloud and drizzle water.

4. Evaluation of spectral dependence of radiative horizontal transport and its effect on near-IR absorption

Using observations made during the ASTEX field campaign and linking the LES explicit microphysics model with a Monte Carlo radiative transfer code, we have simulated a field of highly inhomogeneous broken stratocumulus clouds. It was demonstrated that the small-scale (of the order of 100 m) variance of the horizontal transport depends significantly on the wavelength. In particular, the cloud droplet absorption at λ=1.65 μ can increase the variance of horizontal transport, *var(E)*, by as much as 20%, while the water vapor absorption at λ = 0.94 can result in up to 15% decrease in *var(E)*. These findings indicate that estimates of spectral absorption in the near-IR using the values of horizontal transport outside the absorption interval (e.g. in the visible range) may be quite inaccurate (e.g., in the case of a broken cloud field, the errors at λ=1.65 μ, can be as large as 100%). However, we demonstrated that averaging of radiative parameters on a scale exceeding 500m, would lead to a much weaker spectral dependence of horizontal transport. As a result an accurate absorption estimate in the near-IR can be obtained by using the averaged values of horizontal transport in the visible range. The averaging is especially important when absorption is estimated using data from high-resolution satellites, such as, e.g., LANDSAT.

IMPACT

The improved parameterization of the physical processes in marine stratocumulus clouds will result in a more accurate numerical weather prediction for Navy operations. In particular, we expect an improved prediction of precipitating cloud layers, cloud optical and radiative parameters. The proposed approach for development of physical parameterizations using LES model data verified against observations is appropriate for other investigations.

TRANSITIONS

The CIMMS drizzle parameterization is implemented into COAMPS model as part of the MURI Grant to the University of Oklahoma. Our results have been reported at three scientific meetings, published in refereed journals (4 papers) and conference proceedings (10 papers) and, thus, are well known to the scientific community.

RELATED PROJECTS

The study is aimed at development of physical parameterizations for cloud scale (LES) models. It is related to the ONR project "Remote sensing and prediction of the coastal marine boundary layer" (N00014-96-1-1112) awarded to the University of Oklahoma under the MURI program. The latter goal is to develop and implement physical parameterizations into mesoscale prediction models, in general, and COAMPS, in particular.

REFERENCES

Martin, G. M., D. W. Johnson, and A. Spice, 1994: The measurment and parameterization of effective radius of droplets in warm stratocumulus clouds. *J. Atmos. Sci*., **51**,1823-1842.

McFarquhar G.M. and A.J. Heymsfield, 2000: Microphysics of clean and polluted clouds in the Indian ocean region: observations and parameterizations. *Proceedings of the 13th International Conference on Clouds and Precipitation*, Reno, NE, 14–18 August, 2000.

O'Dowd, C. D., M. H. Smith, A. D. Kaye, and J. Lowe, 1996: The relative importance of NSS-sulfate and sea-salt aerosol to the marine CCN population, *12th International Conference on Clouds and Precipitation*, 19-23 August 1996, Zurich, Switzerland, 334-337.

PUBLICATIONS

Kassianov, E. I. and Y.L. Kogan, 2001: Spectral dependence of radiative horizontal transport in stratocumulus clouds and its effect on near-IR absorption. To be submitted to *J. Geophys. Res.*

Kogan Z. N., and Y. L. Kogan, 2001: Parameterization of drop effective radius for drizzling stratiform clouds, *J. Geophys. Res*, **106**, No. D9, 9757-9764.

Liu, Q., Y.L. Kogan, D.K. Lilly, D.W. Johnson, G.E. Innis, P.A. Durkee, K. Nielson, 2000: LES modeling of ship track formation and its sensitivity to boundary layer structure. *J. Atmos. Sci.*, **57**, 2779-2791.

Khairoutdinov, M. and Y. L. Kogan, 2000: A new cloud physics parameterization for large-eddy simulation models of marine stratocumulus. *Mon. Wea. Rev*., **128**, 229-243.

Shprits, Y, 2000: The effect of sea-salt aerosols on stratocumulus cloud microstructure and drizzle. M.S. Thesis, The University of Oklahoma, 58 pp.

Belochitsky, A, 2001: The cloud physics parameterization for marine stratocumulus based on full moments of the drop distribution function. M.S. Thesis, The University of Oklahoma. To be defended in the Fall of 2001.